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Simulation of shoot emergence pattern of cogongrass (*Imperata cylindrica*) in the humid tropics

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Cogongrass is a noxious perennial grass that has invaded many countries in the tropical and subtropical regions of the world. Its management has been a significant challenge because of large rhizome and bud reserves in the soil. The emergence pattern of this weed under field conditions has received little attention. Field trials were conducted in 2002 and 2003 in the humid forest zone of southeastern Nigeria to model shoot emergence. The experiment had four treatments: (1) count and tag crop-free cogongrass shoots, (2) count and suppress crop-free cogongrass shoots with paraquat, (3) count and cut crop-free cogongrass shoots, and (4) count and cut cogongrass shoots in cultivated corn. The rationale for these treatments was to determine the effect of different monitoring techniques on shoot emergence of cogongrass. The development of the model was based on hydrothermal time, which was calculated from soil moisture and soil temperature at a 2-cm depth. A Weibull function was fitted to cumulative percent shoot emergence values of Treatment 4 and hydrothermal time. The model closely fit the observed pattern of cogongrass shoot emergence ($r^2 = 0.95$, $n = 36$). It also predicted shoot emergence satisfactorily in six treatments ($r^2 > 0.85$, $P < 0.001$, $n = 7$ in each treatment) that simulated farmers' practices in southwestern Nigeria. This is the first model developed for cogongrass shoot emergence based on hydrothermal time under field observations. The model should facilitate further analyses of cogongrass emergence patterns and the timing of its management.

Nomenclature: Paraquat; cogongrass, *Imperata cylindrica* (L.) Beauv. IMPCY; corn (maize), *Zea mays* L.

Key words: Hydrothermal time, model, shoot emergence, soil moisture, soil temperature, tropical weed.

Cogongrass is a C_4 perennial grass that has invaded many countries in the tropical and subtropical zones of the world (Dozier et al. 1998; Holm et al. 1977). Although it produces seeds, rhizomes are its primary mechanism for local regeneration and spread (Dozier et al. 1998). It affects several crops including plantation crops, orchards, and grazing lands (Chikoye et al. 2000; Jose et al. 2002). In Asia, cogongrass has been shown to retard the growth of rubber [*Hevea brasiliensis* (Willd. ex Adr. Juss.) Muell. Arg.] up to 96% within a period of 5 yr (Soedarsan 1980). In West Africa, yield losses of 62 to 80% have been reported in corn and cassava (*Manihot esculenta* Crantz) infested with cogongrass (Akobundu and Ekeleme 2000; Chikoye et al. 2001; Koch et al. 1990; Udensi et al. 1999).

Although the use of planted tree and herbaceous fallow, selected herbicides, and tillage (Anoka et al. 1991; Avav 2000; Chikoye and Ekeleme 2003; Chikoye et al. 2002; MacDicken et al. 1997; Terry et al. 1997; Udensi et al. 1999) has been shown to suppress cogongrass, long-term control remains unsuccessful because of large rhizome and bud reserves in the soil. Traditionally, most farmers (82%) in developing countries, especially in West Africa, depend on manual practices such as hand hoeing or slashing to manage the weed. These management practices usually are repeated three to five times in one growing season to obtain an economic yield (Chikoye et al. 1999, 2002). Even in circumstances where tree or herbaceous species are used to smother the weed, two to three weedings after planting are often required for the fallow species to establish (Chikoye and Ekeleme 2003; Versteeg and Koudokpon 1990). Competing seasonal labor demands often result in delayed manual weeding and cause crop yield losses. Repeated tillage plus herbicide application has been suggested for longer term control (Dozier et al. 1998), but this may not be a viable option for many small-scale farmers because of financial constraints (Chikoye et al. 1999). Also, in large-scale farms, the nonselective herbicides, imazapyr and glyphosate, which suppress cogongrass temporarily (Craig et al. 2003; Miller 2000), are inappropriate in established crops. One approach to improve cogongrass control would be to better understand its biology, especially its emergence behavior in cropped fields. Effective cogongrass management should integrate existing control options with knowledge of field emergence patterns. Currently, very little information exists on seed germination or shoot emergence characteristics of this weed (Mohamad et al. 1989; Tripathi and Amal 1995; Wilcut et al. 1988).

Several studies have demonstrated the effect of early emergence of weeds relative to the crop on yields (Chikoye et al. 1995; Knezevic et al. 1997; Moechnig et al. 2003). For example, Knezevic et al. (1997) reported that the time of redroot pigweed (*Amaranthus retroflexus* L.) emergence relative to sorghum [*Sorghum bicolor* (L.) Moench] leaf stage was critical for the outcome of sorghum–pigweed competition because significant sorghum yield losses occurred when redroot pigweed emerged before the crop's five-leaf stage.

Moechnig et al. (2003) associated corn yield loss to early emergence of common lambsquarters (*Chenopodium album* L.) relative to corn emergence. Early emergence of large crabgrass (*Digitaria sanguinalis* L.) and redroot pigweed in peppers (*Capsicum* spp.) substantially reduced fruit production compared with later emerging weeds (Ashley 1999).

Most of these studies have concentrated on annual weed species. One crucial step to controlling cogongrass in crop would be to understand its field emergence pattern. Farmers need to know the timing and extent of weed shoot emergence before and during the growing season. Such knowledge would enable farmers to allocate weed management resources more efficiently and more likely achieve sustainable cogongrass control.

A number of models for predicting weed emergence patterns of some weed species have been developed (Forcella 1998; Grundy and Mead 2000; Oryokot et al. 1997a, 1997b; Roman et al. 2000). The first-generation models for predicting weed emergence were based on the concept of thermal time or growing degree days (Alan and Wiese 1985; Bewick et al. 1988). With this model, mean daily air or soil temperatures are accumulated until emergence occurs. Satorre et al. (1985) were the first to accomplish this for a perennial weed, johnsongrass [*Sorghum halenpense* (L.) Pers.]. Recent weed emergence models are based on the concept of integrating soil water potential and soil temperature, i.e., hydrothermal time (Forcella 1998; Grundy 2003; Roman et al. 2000), and these models have achieved some level of success (Forcella et al. 2000). However, most of the models developed to understand and predict weed emergence are for temperate annual weed species. Very little has been published on emergence prediction of tropical weeds, especially perennial species. In fact, whether the major variables affecting emergence, such as soil temperature, in tropical species are the same as those in temperate species is not yet known. Currently, very little information exists on the shoot emergence characteristics of perennial weeds. Consequently, there are both practical and basic scientific reasons to understand field emergence patterns of cogongrass.

The objective of this study was to model field emergence patterns of cogongrass and to validate the model against emergence data from selected cropping systems.

Materials and Methods

Field Experiments Used for Model Development

Cogongrass shoot emergence data used for developing the model were collected in 2002 and 2003 from a field infested with natural populations of cogongrass at Umudike, southeastern Nigeria (5°22′N, 7°30′E). Umudike is located in the humid forest zone with 2,351 mm average annual rainfall and 27 C annual mean temperature. The soil is sandy clay loam (Dystric Luvisol; 77% sand, 12% clay, 11% silt, < 1% organic matter, 5.7 pH). The experimental site had been under cogongrass fallow for 2 yr before it was cultivated in 2002. The experiment was established as a randomized complete block design, with four treatments, the first three of which were crop free: count cogongrass shoots and tag, count and remove cogongrass shoots, count and spray shoots with paraquat at 0.45 kg ai ha^{-1}, and count and remove cogongrass shoots in corn. The rationale for using these treatments was to determine whether the monitoring technique (i.e., shoots left intact or removed) affects subsequent shoot emergence in cogongrass. Each plot was slashed manually and hoe tilled (< 10-cm soil depth) on April 5 and 6, 2002, and March 28 and 29, 2003. Each plot measured 4 by 6 m and was separated by a 1.5-m alley from adjacent plots. Corn was sown on April 8, 2002, and March 30, 2003, at a density of 40,000 plants ha^{-1} in rows that were 100 cm apart and at a within-row spacing of 25 cm. Fertilizer was applied at the rate of 90 kg N ha^{-1} (45 kg NPK at planting and 45 kg N urea at 6 wk after planting). All treatments had four replications.

Shoot emergence was monitored in four 50- by 50-cm permanent quadrats in each plot, and percent cumulative cogongrass shoot emergence for each experiment-year was calculated and normalized to 100% for each plot. Seedlings of other weed species in the quadrats were removed. Each plot was weeded four times, with the exception of the quadrats, to prevent cogongrass–corn competition. Cogongrass assessment was done weekly starting on April 15, 2002, and April 7, 2003. Daily air temperature and rainfall data were collected from the National Root Crop Research Institute Meteorological Station located close to the experimental site.

Model Development

Soil moisture and soil temperature were simulated at five depths (2, 4, 5, 10, and 15 cm) with the simultaneous heat and water (SHAW) model (Flerchinger 2000). These depths were chosen because cogongrass rhizome and bud reserves extend deeply in soil (Anoka et al. 1991; Tominaga et al. 1989), and the best soil depth for modeling purposes was not known. Daily maximum and minimum air temperature, dew point, wind run, rainfall, and solar radiation were used as microclimate input variables in the SHAW model. Soil physical input variables used in the model were clay 12%, sand 77%, silt 11%, organic matter 0.42%, and bulk density 1.1 g cm^{-3}. In the model, initial soil temperature and water content were set at 30 C and 0.01 cm^{3} cm^{-3}, respectively.

The development of the emergence model was based on the hydrothermal time (θ_{HT}) concept, defined as an integration of hydrotime (θ_H) and thermal time (θ_T). Hydrothermal time is described more formally (Roman et al. 2000) as:

$$\theta_{HT} = (\Psi - \Psi_b)(T - T_b), \quad [1]$$

where $\theta_H = 1$ when $\Psi > \Psi_b$ otherwise $\theta_H = 0$; $\theta_T = T - T_b$ when $T > T_b$ otherwise $\theta_T = 0$. Soil water potential is represented by Ψ, Ψ_b is base soil water potential, T is temperature, and T_b is base temperature.

T_b (25 C) and Ψ_b (−0.01 MPa) were determined by iterating a set of temperatures (20 to 30 C, at 1 C intervals) and water potentials (−0.10 to −0.01 MPa, at 0.01 MPa intervals) in Equation 1 until there was a maximal fit between hydrothermal time and percent cumulative emergence for each of the experiment-years. The temperature and water potential values used in the iterations were based on (1) monthly air temperature ranges at the experimental site and (2) earlier controlled germination studies on cogongrass (Tripathi and Amal 1995; Wilcut et al. 1988). In growth chamber studies, these authors found that cogongrass seeds germinate at 32.6 to 36.2 C (within April to September), whereas rhizomes sprouted at day/night temperature regimens of 30/25 C and 27/22 C. Hydrothermal time was accumulated for each experiment-year as:

$$\theta_{HT} = \sum_{d=1}^{i} \theta_H \theta_T \quad [2]$$

Hydrothermal time started accumulating on March 11, 2002, and February 21, 2003, the dates of full soil tillage before crop planting. To predict the pattern of shoot emergence, the percent cumulative emergence values were fitted to the Weibull function:

$$Y = M[1 - \exp(-k(\theta_{HT} - z)^c)], \quad [3]$$

where Y is the cumulative percent emergence at hydrothermal time (θ_{HT}), M is the asymptote (theoretical maximum for Y normalized to 100%), k is the rate of increase, z is the lag phase, and c is a curve shape parameter. For estimation purposes, k was parameterized as $k = (1/a)^c$. The parameters (a and c) in the Weibull function were estimated by a nonlinear regression procedure (PROC NLIN) that used the Gauss–Newton algorithm in SAS (1995). The function was initialized with k and c set to 0.001 and 1.95, respectively. The Weibull function was chosen in preference to similar equations (e.g., logistic) because it does not assume symmetry on either side of a midpoint (i.e., 50% emergence) and there is no obvious biological reason to presume such symmetry for shoot emergence.

Model Evaluation in Ibadan

Cogongrass shoot emergence values were collected from a research-managed on-farm trial that started in 1996 and continued through 2000 on a site heavily infested and abandoned to cogongrass at Ibadan, southwestern Nigeria (7°35′N, 3°55′E). Mean annual rainfall is between 1,200 and 1,500 mm, whereas annual mean temperature is 26 C. Soil type at the experimental site was sandy loam (Oxic Paleustalf) with 86% sand, 5% clay, 8% silt, 0.67% organic matter, and pH 6.5. Chikoye and Ekeleme (2003) described in detail the cropping history and part of the experimental design. In this analysis only shoot emergence values collected in 1998 were used because the assessment period was much longer than those in other experimental years. In 1998, there were three main-plot treatments: corn, cassava, and corn–cassava intercrop. Selected cover crops and two hand-weeding regimens (weeded twice and weeded five times) were the subplot treatments. Hand-weeded treatments were used in the analysis. These treatments were used because they simulated the farmers' cogongrass management practices in the region.

Subplot size was 5 by 10 m, and each was replicated four times. Corn and cassava were planted at 40,000 and 10,000 plants ha^{-1}, respectively. Fertilizer was applied at the rate of 90 kg N ha^{-1} (45 kg NPK at 2 wk after planting and 45 kg N urea at 6 wk after planting). Each plot was tilled.

Cogongrass shoot emergence was assessed every 3 to 4 wk starting on May 4 in four 50- by 50-cm quadrats in each subplot. Cogongrass shoots in each quadrat were counted and clipped at ground level. Each quadrat was relocated to another point in the plot in subsequent assessments.

Results and Discussion

Field Observations for Emergence Model Development

Cogongrass shoot emergence in Umudike was low at the onset of monitoring in April. Cumulative emergence rose to 50% within 5 wk, at about 38 θ_{HT}, in all the treatments in 2002 (Figures 1a–c), except in the count and tag treatment, where about 50 θ_{HT} elapsed (Figure 1d). The rate of shoot emergence was different in 2003 compared with that in 2002. For example, 50% shoot emergence occurred much earlier, within 3 wk, at 19 θ_{HT}, in count and tag treatment (Figure 1h). In the other treatments, where cogongrass shoots were either sprayed with paraquat or physically removed after counting, 50% shoot emergence was reached within 10 wk, at 47 θ_{HT}, in 2003 (Figures 1e–g). We attributed this trend in emergence to tillage effects, i.e., the two tillage operations occurring by 2003 may have affected the distribution of rhizome reserves in the soil, thereby resulting in a slower rate of emergence in 2003. Several authors have shown that repeated tillage suppresses cogongrass (Akobundu and Ekeleme 2000; Anoka and Froud-Williams 1995; Dozier et al. 1998). Furthermore, tillage fragments rhizomes into small sections that have reduced vigor or die if exposed at the soil surface. Rhizome fragments lose viability readily on drying (Ivens 1980). In each experiment-year, the pattern of shoot emergence was similar except in treatments where cogongrass was counted and allowed to grow (Figures 1d and 1h). The presence of corn also did not have any significant influence on the pattern of shoot emergence in either year (Figures 1a and 1e). This result supports the finding of Roman et al. (2000) for an annual temperate species.

In summary, 50% emergence of shoots, in treatments where shoots were removed after counting, consistently occurred between 38 and 47 θ_{HT}. In contrast, where shoots were allowed to grow, 50% emergence was delayed in 2002 but accelerated in 2003 relative to other treatments. These differences in emergence patterns may reflect the effects of canopy shading and soil water use by intact cogongrass plants, variables for which we cannot account in our current simulations of θ_{HT}.

At Ibadan, the presence of corn, cassava, or corn–cassava did not influence the pattern and magnitude of shoot emergence (Figure 2). No definite trend was associated with main-plot treatment (crop type) or weeding regimen. However, up to 25% shoot emergence occurred within 8 wk after crop planting at 20 θ_{HT}, except in cassava plots weeded five times. In this latter treatment, 25% shoot emergence occurred within 9 wk after crop planting at 20 θ_{HT}. In all treatments and both years, 50% emergence occurred at about 27 to 30 θ_{HT}. Complete shoot emergence occurred at < 65 θ_{HT} at both locations.

Hydrothermal time at soil depths lower than 2 cm was unable to describe shoot emergence accurately when comparing between years. This conclusion is illustrated in Figure 3 through comparisons of emergence (dependent variable) for 2002 and 2003, with θ_{HT} (independent variable) calculated at soil depths of 2, 4, 5, 10, and 15 cm. At depths greater than 2 cm, observed emergence relationships for 2002 and 2003 appeared unique. However, when emergence was plotted against θ_{HT} at 2-cm soil depth, the data for

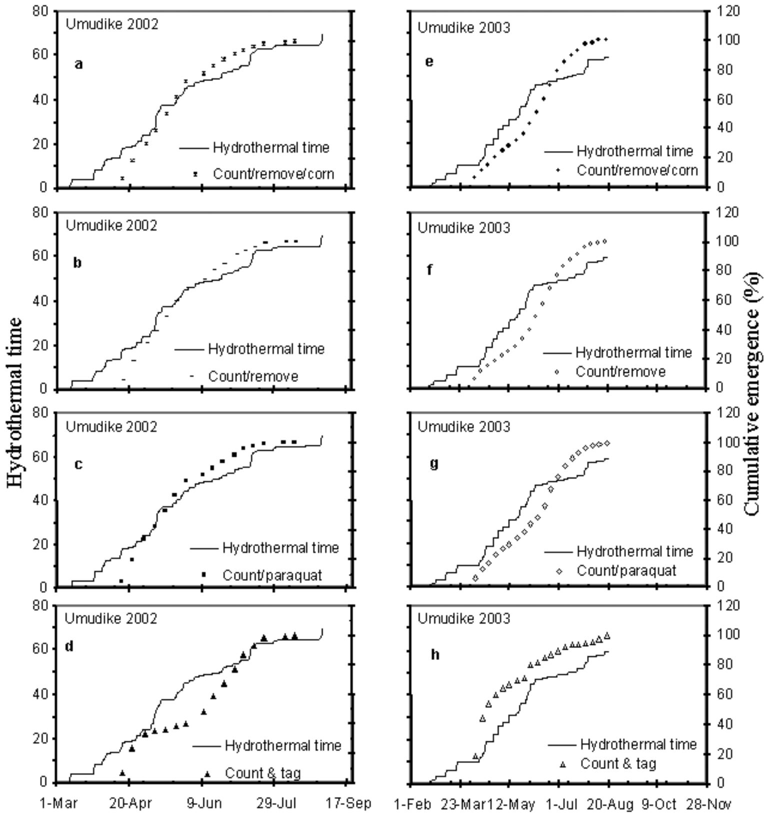

FIGURE 1. Cumulative hydrothermal time at 2-cm soil depth and cumulative percent shoot emergence of cogongrass in 2002 and 2003 at Umudike, southeastern Nigeria. For calculating hydrothermal time, base soil temperature and base soil water potential were set at 25 C and −0.01 MPa, respectively. Cogongrass shoot emergence was monitored by counting and removing shoots in corn (a, e), counting and removing shoots in crop-free plots (b, f), counting and suppressing shoots with paraquat in crop-free plots (c, f), and counting and tagging intact shoots in crop-free plots (d, g).

both years merged into an apparent single relationship more so than at any alternative depth. This result suggests that although large rhizome and bud reserves in the soil extend down to a 30-cm depth (Anoka et al. 1991; Tominaga et al. 1989), the 2-cm depth might be the appropriate depth to study and model cogongrass emergence. The reason for this is that shoot emergence of cogongrass tends to be successful only from rhizomes buried within the top few centimeters of the soil (Mohamad et al. 1989; Wilcut et al. 1988). For example, in a growth chamber study, cogongrass shoot emergence was highest for rhizomes buried at 2- to 4-cm soil depth, decreased to 17% for rhizomes buried at 8-cm depth, and was absent for rhizomes buried at 16-cm depth (Wilcut et al. 1988). These studies also showed that

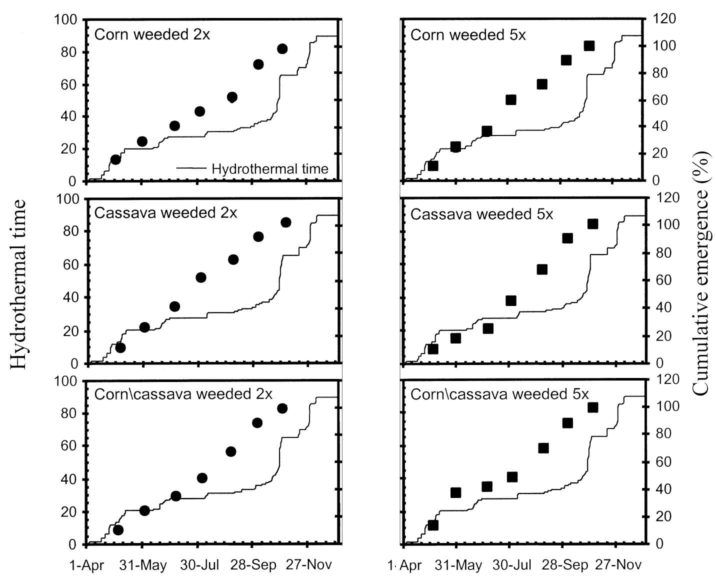

FIGURE 2. Cumulative hydrothermal time at 2-cm soil depth and cumulative percent shoot emergence of cogongrass in 1998 at Ibadan, southwestern Nigeria. Cogongrass shoot emergence was monitored in corn, cassava, and a corn–cassava mixture. Each crop was weeded two or five times.

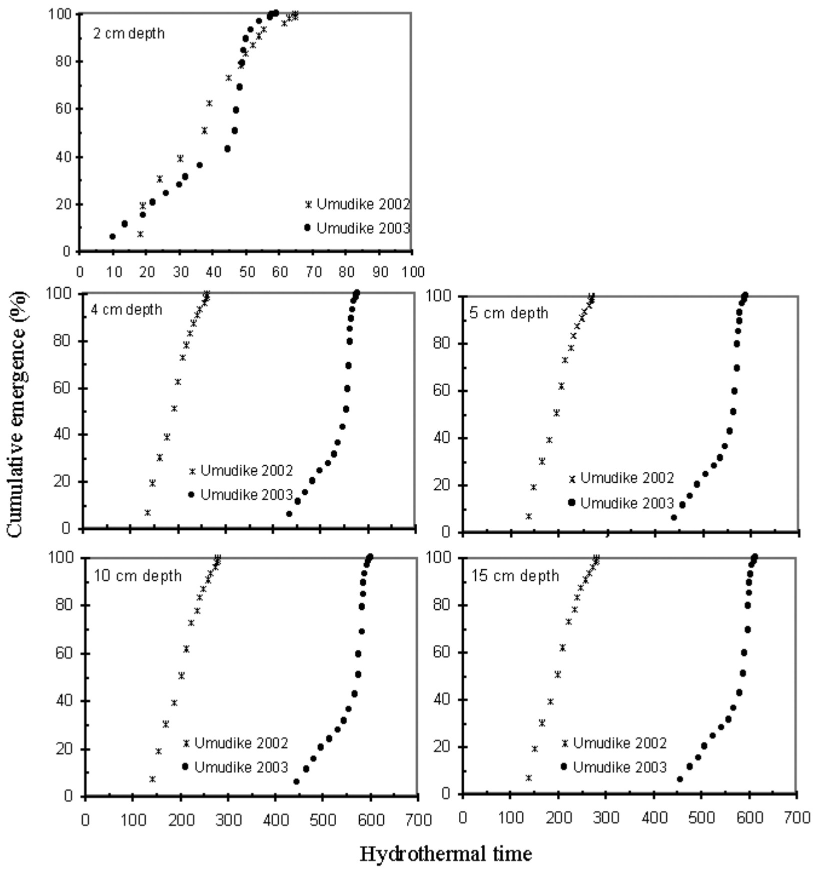

FIGURE 3. Cumulative percent shoot emergence of cogongrass as a function of hydrothermal time at different soil depths at Umudike, southeastern Nigeria. Note that only when hydrothermal time at 2-cm depth is accumulated do the data from 2002 and 2003 merge, indicating that hydrothermal time at 2-cm depth may be a better predictor of emergence than hydrothermal times calculated from other soil depths.

emergence started after 30 d for rhizome sections buried at 2-cm depth.

Model

Cogongrass shoot emergence was described accurately by the emergence curve from the 2-cm soil depth hydrothermal time model (Figure 4). Predicted shoot emergence values and field emergence observations were correlated significantly (r^2 = 0.95, n = 36). Shoot emergence in the treatment sown to corn was used to fit the model because it represented the practice used by the majority of farmers in southwestern Nigeria. The model predicted 50% shoot emergence at 37 θ_{HT}. This prediction agreed with field emergence in 2002 (0 to 35 d after crop planting). In 2003, 50% shoot emergence was reached at 47 θ_{HT} (0 to 70 d after crop planting) in a similar treatment. An emergence level of 85% was predicted at 50 θ_{HT}, and this agreed with field observations in both years.

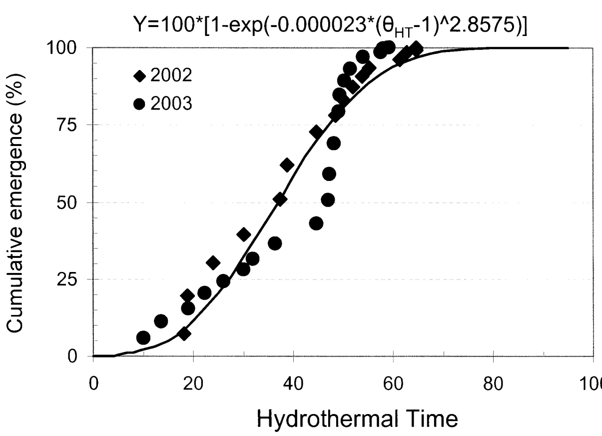

FIGURE 4. The distribution of cogongrass shoot emergence with hydrothermal time at Umudike in 2002 and 2003 fitted to a Weibull function. For calculating hydrothermal time, base soil temperature and base soil water potential were set at 25 C and −0.01 MPa, respectively.

Model Evaluation

The model was evaluated against shoot emergence data sets from six different treatments that simulated farmers' practices in the region. The cumulative emergence values from each treatment were regressed against the predicted values. The regression coefficients were used to test how good the predicted values fit observed field emergence. The model predicted shoot emergence closely in all six treatments tested ($r^2 > 0.85$, $P < 0.001$, $n = 7$ each treatment) (Figure 5). Canopy density and closure varied with the type of crop planted (F. Ekeleme, personal observation), but the model fit to the observed field emergence was similar in all treatments irrespective of crop type or number of weedings.

Our results represent the first model developed for cogongrass shoot emergence based on soil hydrothermal time and field observations in humid tropical environments. Be-

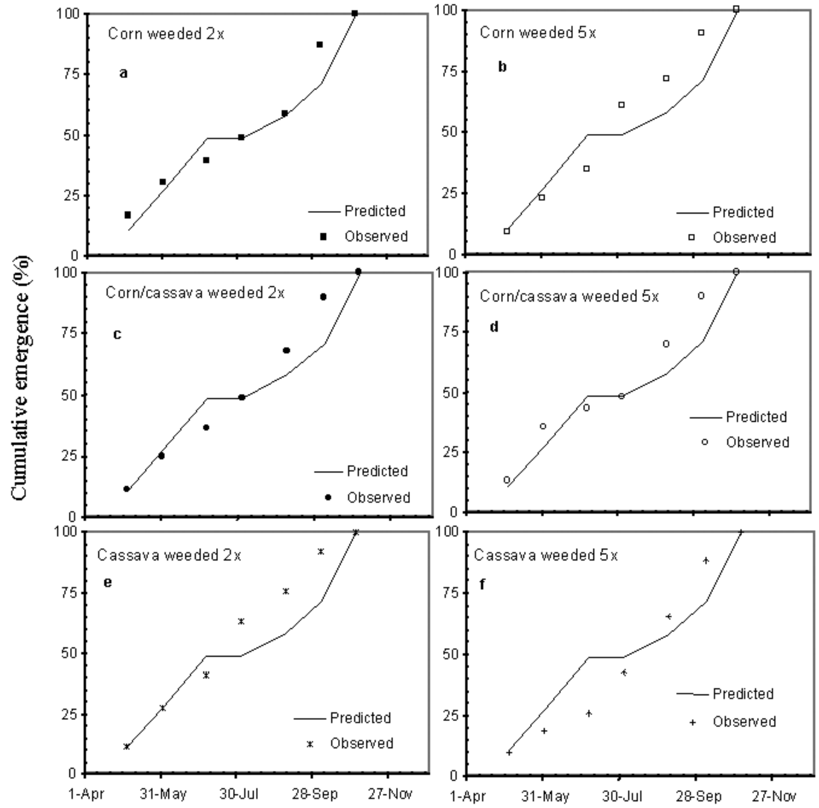

FIGURE 5. Simulated and observed cogongrass shoot emergence at Ibadan in (a) corn weeded twice, (b) corn weeded five times, (c) corn–cassava weeded twice, (d) corn–cassava weeded five times, (e) cassava weeded twice, and (f) cassava weeded five times.

cause its simulations were evaluated against six independent data sets and agreed relatively closely with them, the following can be concluded. (1) Shoot emergence of this tropical, rhizomatous, and perennial plant appears to respond to hydrothermal time in the same general fashion as temperate plants. Although the estimated base soil temperature (25 C) and base soil water potential (-0.01 MPa) for cogongrass shoot emergence are higher than those of many temperate species, the process of modeling shoot emergence of tropical species probably does not differ from that of temperate plants. (2) The model seems to have some merit; consequently, it may have the potential to aid further analyses of cogongrass emergence patterns. (3) Accurate simulation of cogongrass shoot emergence should facilitate new weed control experiments, such as hand hoeing or herbicide application at predetermined levels of shoot emergence. This might ultimately lead to new and practical recommendations regarding the best times for sustained control of cogongrass in farming systems of the humid tropics.

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